NANOSTRUCTURED ORIGAMI™ 3D FABRICATION AND SELF ASSEMBLY PROCESS FOR SOLDIER COMBAT SYSTEMS

William J. Arora*, Hyun Jin In, Tilman Buchner, Yang Shao-Horn, Henry I. Smith, George Barbastathis
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

The Nanostructured Origami™ 3D Fabrication and Assembly Process is a method of manufacturing 3D nanosystems using exclusively 2D lithography tools. The 3D structure is obtained by folding a nanopatterned 2D substrate. We report on the materials, actuation and modeling aspects of the manufacturing process, and present experimental results from fabricated structures.

1. INTRODUCTION

Two-dimensional (2D) nanopatterning can reliably produce features in the range of 10-40nm using electron beam and x-ray lithography, nanoimprinting and dip-pen lithography. These methods are well suited to planar nanoelectronics and other applications where 2D feature layouts are sufficient. However, building nanostructures in the third dimension (3D) enables new functions unreachable with 2D processing. Three-dimensional nano-fabrication and assembly remain challenging because of the lack of parallel (in-line) manipulation tools that would allow the placing of components in their proper places. The Nanostructured Origami™ process [1] assembles 3D systems with component features ranging from the nanoscale to the millimeter scale by using exclusively 2D lithographic tools. The process (analogous to the Japanese art of "origami") involves patterning adjacent 2D membranes that can be lifted off (using methods we have developed) of a silicon substrate and folded to create useful 3D structures. This can be done easily and cost-effectively by many commercial and research-grade methods. This innovative process holds immense potential for the Army's Objective Force Warrior. Nanostructured Origami enables many practical and promising technologies that will allow soldiers to be safer and more effective in a wider variety of situations. Examples of useful devices we are fabricating include supercapacitors for efficient energy storage [2], identification systems to prevent friendly fire, optical signal transmission devices for high density data storage and high speed data transmission, and chemical/biological sensors that are directly integrated with electronics and other MEMS components.

2. FABRICATION TECHNIQUES

We have developed two self-assembling folding schemes to realize 3D on chip devices, stress actuated folding and magnetic force actuated folding. Magnetic force folding uses gold wires as hinges, making it well suited for electrical applications. Stress actuated folding is a more versatile technique because no external forces or fields are required to actuate the folding.

2.1 Stress Actuated Folding

The stress actuation method is a way to fold thin films (sub micron thickness) into simple 3D shapes such as corner cubes, nanotubes, and raised bridges. This is achieved by defining a bilayer strip of length l in the region where folding is to take place (Figure 1). The upper layer of these hinge areas is intentionally deposited with as much residual stress as possible. This intrinsic stress causes the hinge to curl in a predictable fashion when released from the substrate, which is what folds the lower structural layer.

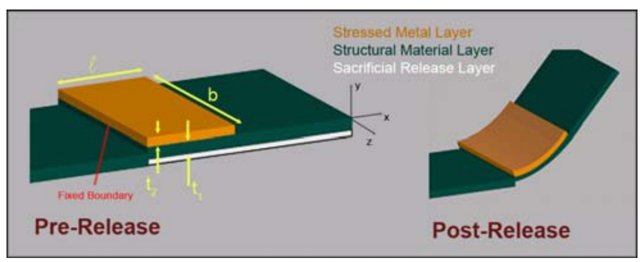

Figure 1. Schematic of the stress actuated folding method. Layer 1 is the structural (lower) layer and layer 2 is the stress (upper) layer.

We can predict the curling radius of the thin films, and therefore design each hinge to fold to a specific angle by adjusting its length. We have modeled the bilayer hinge structures as thin plates and applied beam bending theory to derive an expression for ρ, the radius of curvature. This formula has also been derived in [3].

$$\rho = \frac{1}{k} = \frac{E_1'^2 t_1^4 + E_2'^2 t_2^4 + 2E_1'E_2't_1t_2(2t_1^2 + 2t_2^2 + 3t_1t_2)}{6E_1'E_2't_1t_2(t_1+t_2)\cdot \varepsilon_{tot}^i},$$

where

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Nanostructured Origamitm 3d Fabrication And Self Assembly Process For Soldier Combat Systems**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology Cambridge, MA 02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

$$E_i^{'} = \frac{E_i}{1-\nu^2}; i = 1,2$$

Radius of curvature is a function of material properties, thickness, and initial strain. $E_i^{'}$ is elastic modulus, t_i is layer thickness, ε^{i}_{tot} is initial strain due to residual stress in layer 2.

The two materials of interest for our structural layer are silicon nitride and silicon dioxide. They can be deposited without residual stress and are often used in optical MEMS. We have used chromium for our stressed metal layer because it can be evaporated with more than 2 GPa of tensile stress, and because it is highly etch selective. In our experiments, we show results using silicon nitride and chromium bilayers. With these material properties, and fixing the thickness of the silicon nitride layer to 200nm, we can observe how the thickness of the chromium layer (t_1) affects the radius of curvature (Figure 2).

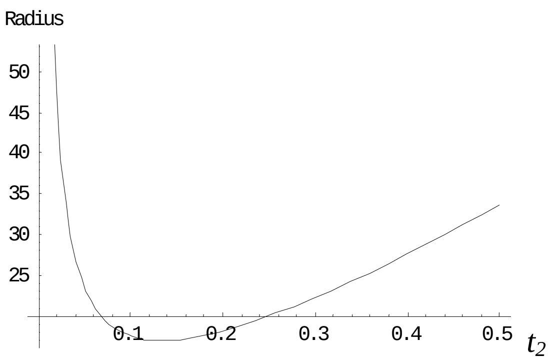

Figure 2. To obtain a minimum radius, t_2 should be between 110 – 150nm. The radius will be ~18 µm.

In section 3.1, we show our experimental results that closely agree with our theory.

2.2 Magnetic Force Actuated Folding

Magnetic force actuated folding is another method of folding the membranes without the need for manual assembly [1]. When an external magnetic field parallel to the substrate is applied to a section of the device with a current loop running through it, an upward force is generated by Lorentz law as shown in Figure 3. By controlling the current to individual segments, the amount of force applied to each folding membrane, and thus its motion, can be precisely controlled.

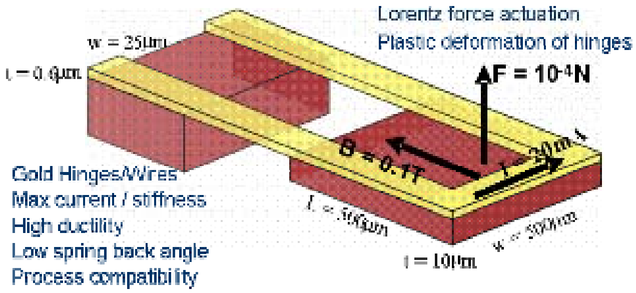

Figure 3. The Lorentz force can be used to raise the desired segment out of plane in the presence of a current loop and a properly oriented magnetic field.

3. FABRICATION RESULTS

We have tested both stress actuated and magnetic force actuated devices in the lab. Both were observed to fold as expected and consistently. The stress actuated folding method is clearly best suited for applications that require devices to be formed on small thin films, and the gold hinge method is best suited for folding thicker and larger devices.

3.1 Stress Actuated Folding Results

We have demonstrated the ability to curl thin films of silicon nitride by patterning hinge areas of stressed chromium [4]. The silicon nitride is deposited by LPCVD, and the chromium is deposited by evaporation. For our initial experiments, we used film thicknesses of 200nm and 110nm respectively. As explained in section 2.1, we expected to see an 18 µm radius of curvature.

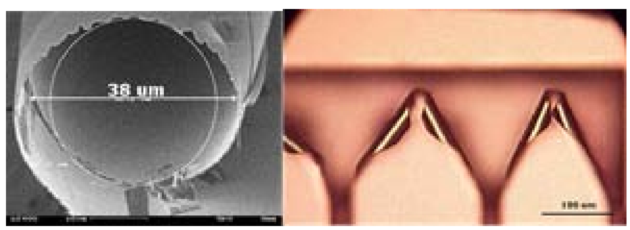

Figure 4. (a) Front view showing 19µm radius (b) Overhead view of release step.

Our first devices were released with a KOH underetch of the silicon substrate. Figure 4b shows how the KOH anisotropic etch affects the release of the stressed metal hinges. Subsequent experiments were performed by rotating the hinges 45^{o} to the silicon crystalline axis. Figures 5a and b show that we were able to release the hinges from the edges instead of the corners with the same KOH etch.

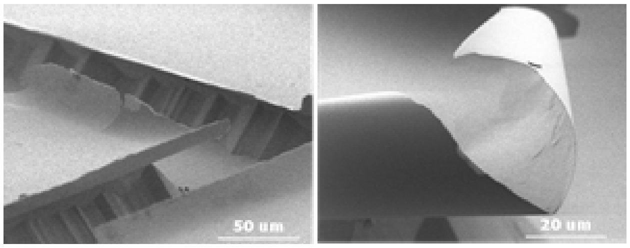

Figure 5. (a) Timed 10 minute etch. (b) Timed 20 minute etch.

Knowing the etch rate of KOH and the radius of curvature for the hinges, we were able to control the angle to which the hinges curled. Figures 5 a and b show timed release etches of 10 and 20 minutes; corresponding to 90^{o} and 180^{o} folds respectively.

3.2 Magnetic Force Actuated Folding Results

Magnetically actuated folding devices have been successfully fabricated using both silicon and SU-8 as structural materials. SU-8 is a type of photoresist used commonly as structural material in MEMS devices due to its robust properties and ease of use. In devices made of silicon, the Lorentz force actuation method was used to achieve up to a 180º fold [1]. Figure 6 shows a 6-segment SU-8 device prior to being folded. The wiring configuration allows the membranes to be folded in an accordion-like fashion.

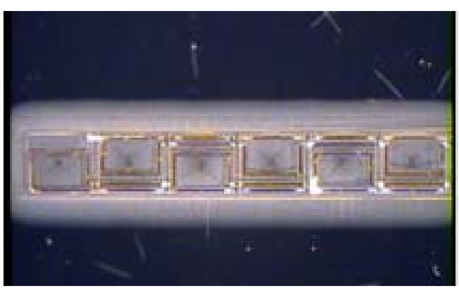

Figure 6. 6-segment SU-8 device prior to magnetic actuation.

4. NOVEL SOLDIER APPLICATIONS

The Nanostructured Origami™ 3D assembly process unlocks a new dimension previously unrealized in semiconductor devices. Many new devices can be created and their applications range across the engineering disciplines. Here we present four soldier combat systems that we are building.

4.1 Supercapacitor

The use of the 3rd dimension allows the creation of microscale, electrochemical devices, such as supercapacitors, that have very large electrode areas but a small areal footprint. For example, an electrochemical device that takes up much space on the chip can be folded to result in a compact, multi-layer, 3D structure (Figure 7). Nanostructured Origami allows such devices to be formed from a single, micro/nanofabricated layer. In addition, nanoarchitecture can be added to any electrode to increase device performance, for example in microscale fuel cells. Finally, the Nanostructured Origami™ process is compatible with most standard microfabrication processes and thus allows for an easy integration of electrochemical devices to pre-existing microsystems. These supercapacitors can be used in conjunction with energy harvesters, for example, to provide a constant source of energy for wireless sensors [5].

The finished device shown in Figure 8 consists of two SU-8 membranes connected with gold hinges, which also serve to electrically connect the electrodes to the power source. Carbon paint is used as the porous electrode material, and the membranes are folded so that the two electrode surfaces face each other, effectively forming one active cell of the supercapacitor.

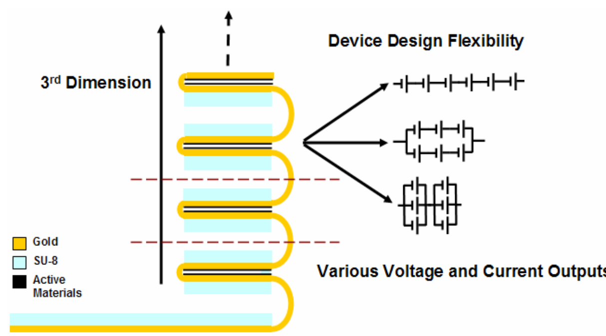

Figure 7. Schematic of a multi-layer supercapacitor with flexible voltage and current outputs.

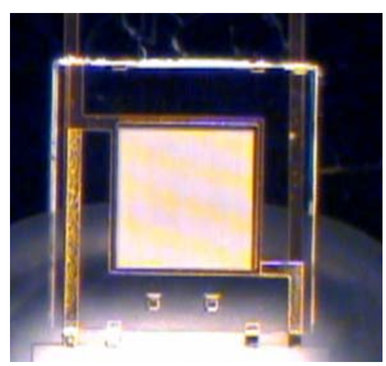

Figure 8. A completely assembled supercapacitor.

4.2 Long Range Soldier ID Tag

One of the easiest structures to fold with the Nanostructured Origami technique – a corner cube – is also one of the most practical. Micron sized corner cube reflectors have been demonstrated as potential long range optical communication devices [reference] because they reflect incident light back to its source. Using Nanostructured Origami, we propose corner cubes as soldier identification tags (Figure 9). These cubes can be probed from long range with the IR lasers that can be mounted on Apache helicopters and alert for friendly targets. The data on the cubes can also be encrypted to prevent enemy data interception.

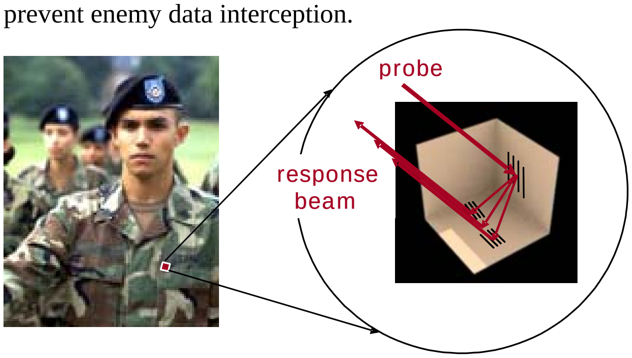

Figure 9. Conceptual diagram illustrating corner cubes patterned with diffraction gratings used as soldier ID tags [6].

The corner cubes are fabricated in three steps. First, diffraction gratings are patterned on each cube face. Second, two folding areas are patterned as either gold wire or stressed metal hinges. Finally, the cubes are released to self-assemble. The unique diffraction grating pattern on each cube is what provides a unique ID. This same grating is what modulates the reflected wavefront of the probe beam.

4.4 Integrated On-Chip Chem / Bio Sensors

Nanostructured Origami is an ideal platform for hybrid systems, combining multiple modalities such as electrical (power), electronic (logic), optical, fluidic, and mechanical (reconfiguration). Such systems are important for a number of applications, out of which sensors stand out as the most promising for the Army. Typically, a sensor system combines several of these modalities in order to transduce chemical or optical signals to electrical, and thus identify potential threats.

The key challenge in such hybrid systems is the assembly of multiple components in their proper positions in 3D space. In macroscopic systems, assembly is performed routinely by robots according to pre-determined sequences of picking up and placing components in the system. At smaller scales, below 10s of microns, this solution can be applied via several micro-nanomanipulation tools which are presently commercially available, but it would be impractical because of the time it would take. Assembling a multi-functional hybrid system via micro-nanomanipulators would be like assembling a modern computer microprocessor via discrete electronic components, even miniature ones – clearly an impractical approach for processors that contain in excess of tens of millions of transistors each. Planar lithographic fabrication is a tenable solution for microprocessors, but it runs into serious limitations in hybrid systems. For example, as the demands from the sensor system increase, so does the required area in the planar solution; beyond a certain point, the 2D implementation becomes impractical. Another important limitation of 2D implementations is the issue of connectivity, namely the transit time of signals (latency) between different points in the system. The problem is particularly acute in electrical and fluidic signals which travel at relatively low speeds. Therefore, a 3D layout is preferable, but presently limited by the 2D nature of lithographic tools.

Nanostructured Origami provides an elegant solution, still based on the exclusive use of 2D litho tools, but capable of assembling in 3D via folding. The system is first designed compactly in 3D, and optimized for volume/surface ratio and latency. It is then subsequently decomposed into its surface elements, and unfolded so that the surface elements find themselves laid out on a surface adjacent to each other. At this point the design phase is complete, and the unfolded system can be fabricated via a standard lithographic method. The final folding step produces the actual 3D system. For example, the supercapacitor structure of section 4.1 and the functionalized corner-cube reflector can be combined with a microprocessor as an additional layer of CMOS electronics to yield a system with its own energy storage, optical sensing, optical telecommunication, and logic capability. Such a system would function as a self-contained miniature, disposable sensor. Other capabilities can be easily added, e.g. by incorporating moving elements one can include power harvesting capabilities, microfluidic pumps for chemical and biological identification, etc.

Note that there is no proof of a general solution to the problem of unfolding a 3D shape to a 2D medium in topologically continuous fashion (i.e., without the need to tear edges or pass segments through each other.) However, common experience with origami art indicates that there is a great variety of spectacular achievable 3D shapes. This gives us confidence that the Nanostructured Origami technique will enable many hybrid systems of practical importance in the future.

5. KINEMATIC MODELING

Modeling the kinematics of origami structures is necessary to verify two desirable properties: (i) integrity, *i.e.* ensure that the structure is not torn at its hinges during folding; and (ii) compatibility, *i.e.* avoidance of collisions between segments during folding. Note that the integrity concern does not arise in robotic manipulators, for example; in origami, it is essential because of the 2D nature of the segments. Prior works have used affine transformations [7] and pseudo-triangulations [8] to model folding and unfolding. We used screw calculus [9] because it is computationally convenient. Its dual twist calculus permits the straightforward derivation of the dynamical model as well.

Our model begins by attaching a closed "skeleton" structure to the origami segments. The skeleton is then broken into two parts and forward kinematics are performed in the part that contains the actuation mechanism. The second part is constrained by the integrity condition, and so its motion is estimated via inverse kinematics. Singularity in the inverse kinematics of the second part indicates that kinematic integrity is violated in the given structure. Kinematic compatibility is ensured by tracking the segment edges (this function has not yet been implemented in our software tool).

Figure 10 shows an example of a five-segment origami structure, and the folding angle progression as the diagonal joint is actuated. Our approach is presently limited to similar single-vertex structures [7, 8].

5. CONCLUSION

In conclusion we have demonstrated preliminary prototypes of Nanostructured Origami and constructed models for its design and analysis. Future work will include demonstrations of applications as discussed in section 3.

This research was funded by the U.S. Army Research Office through the MIT Institute for Soldier Nanotechnologies and by DARPA and Sematech through the Interconnect Focus Center.

REFERENCES

[1] S. M. Jurga et al., "Nanostructured Origami," *Proc. 3rd Int. Conf. on Nanotechnology*, vol. 2, pp. 220-223, 2003.

[2] Y. Shao-Horn et al., "Origami fabrication of electrochemical device on the micrometer scale," 204th Meeting of the Electrochemical Society, Orlando, FL, October 2003 (abstract 1279).

[3] GP Nikishkov, "Curvature estimation for multilayer hinged structures with initial strains." Journal of Applied Physics, 2003, 94(8), pp. 5333-5336.

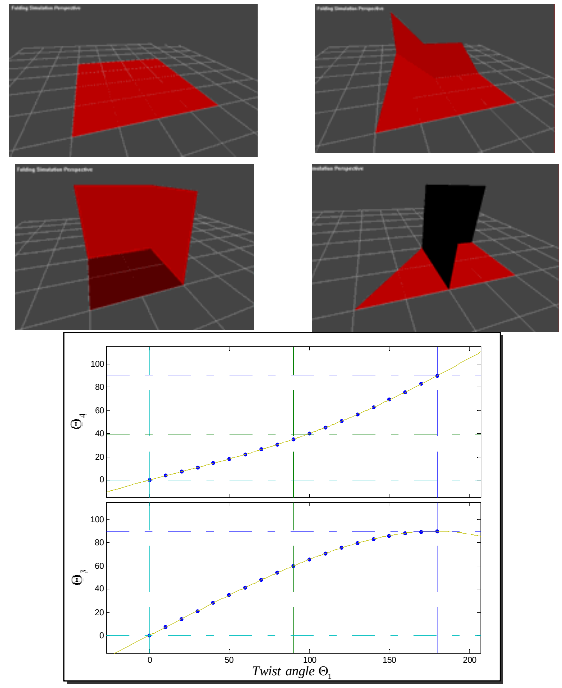

Figure 10. Five-segment origami mechanism (actuation sequence shown clockwise on top) and the folding angles of two of the segments in response to actuation of the diagonal joint.

[4] H. J. In et al., "The Nanostructured Origami™ 3D Fabrication and Assembly Process for Nanomanufacturing," IEEE Nanotechnology 2004, Munich, Germany, Aug 12-14 (paper 8-12).

[5] H.J. In et al., "Fabrication of 3D Nanostructures via Nanostructured Origami™ Process," To appear in the *Proc. 2nd International Symposium on Nanomanufacturing*

[6] Soldier picture taken from: http://www.arng.army.mil/web_images/soldier_resources

[7] s.-m. belcastro, and T. C. Hull, "Modelling the folding of paper in three dimensions using affine transformations," *J. Lin. Alg. and its Apps.*, vol. 348, pp. 273-282, 2002.

[8] R. Hass, et al., "Planar Minimally Rigid Graphs and Pseudo-triangulations," *Proc. ACM Symp. Comp. Geometry (SoCG)* San Diego, CA, pp. 154-163, 2003.

[9] R. W. Brockett, "Robotic manipulators and the product of exponentials formula," *Int. Symp. Math. Theory of Networks and Systems*, Beer Sheba, Israel, pp. 120-129, 1983.